# *Performance Characterization of a Performance Shape Memory Composite Mirror*

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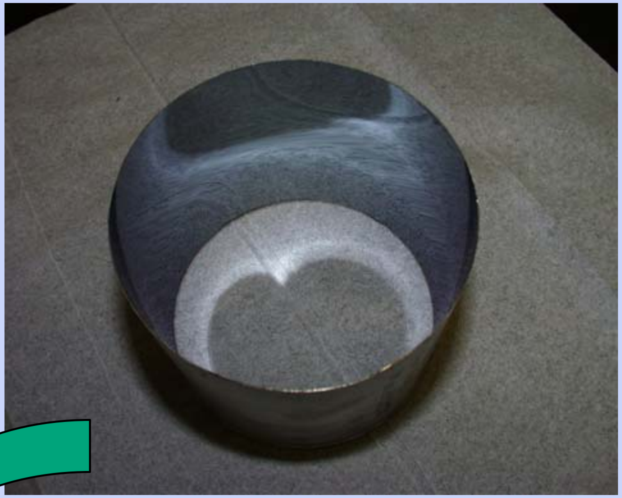
**Ball Aerospace & Technologies Corp.**

**ACT-02-0096**

**Contract NAS1-03007**

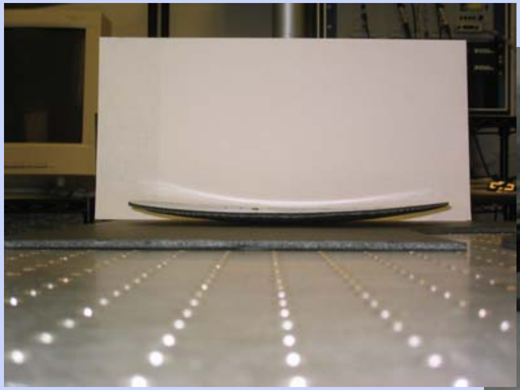
# Laminated Deployable Optics

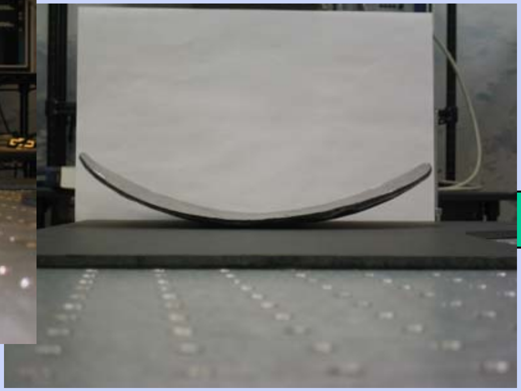
## The Best of Two Technologies

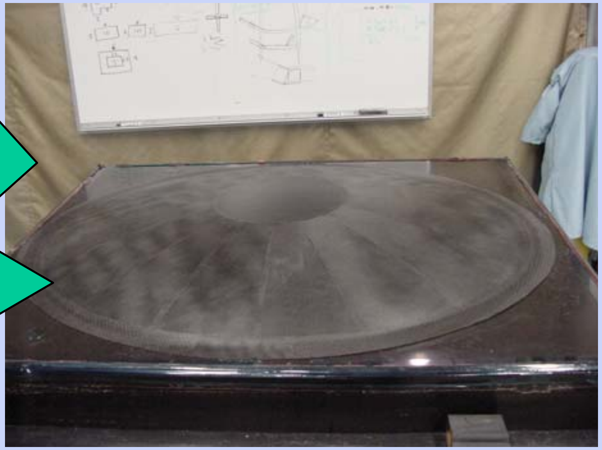


Nickel electroformed replica: Smooth, accurate optical surfaces

Shape memory polymer- carbon fiber reinforced, for light weight and controllable deployment







**Deployable, lightweight reflectors**

# ESSP Needs for Deployable Reflectors

- **ESTO Workshop (2003) identified multiple mission needs for deployable imaging systems requiring apertures of 1 to 5 meters and larger**
  - Microwave- soil moisture, temp radiometry, cloud heights
  - IR- temperature measurement, radiometry
  - SAR
  - Visible- Lasercom, LIDAR

- **Deployable reflectors are an enabling technology for many missions**
  - Lighter weight and stiffer optics
  - Instrument capabilities enhanced at larger apertures
  - Cross enterprise value to OSS, Exploration missions

# Science Enabled by Deployable Optics Technologies

Earth Science Enterprise Technology Planning Workshop 2003

## Light-Weight Deployable UV/Visible/IR Telescopes

### Science Measurements Enabled

- Tropospheric Chemistry
  - High vertical resolution tropospheric O3 , NO2, and aerosol profiles
- Carbon Cycle Budget
  - Profile and column CO2 distributions
- Global Water & Energy Cycle
  - Water vapor, temperature, aerosol, & cloud distributions (active & passive combined)
  - Tropospheric winds (direct & coherent)
- Thermal IR Imaging from GEO, L1, L2
  - High spatial (horizontal) and temporal resolution for rapidly evolving regional scale processes

### Deployable Telescope Tech.

- Telescope Technologies for >5 m2 area
  - Light-weight mirrors composition
    - Glass/Composite
    - Thin film (stretch membrane/replicated shells)
  - Structures and latches
    - Deploy/redeploy capability
    - Elastic Memory Composite materials
  - Optical alignment techniques
    - Active vs. Passive
    - Deformable/Correction optics
- Common Telescope Reqt's and Testing
  - Size, Optical Quality, Wavelength Range, Orbits, Operating Temperatures
- Space Validation Needs
  - Nonlinear behavior in zero g environment

# Deployable Antenna Requirements

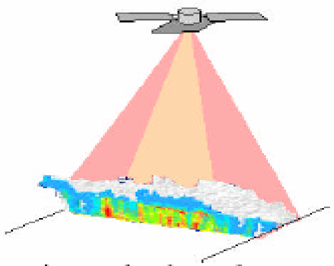
## Requirements for Large, Lightweight Deployable Antennas: Reflector Antennas

### Science / Measurement
- LEO Rain Radar
- Soil Moisture Radiometer
- GEO Rain Radar
- Ocean Salinity
- Ocean Surface Wind Vector

### Missions Enabled/Enhanced
- Soil Moisture Mission
- Hazards Mission
- GPM Follow-on
- Ocean Salinity

### Description of Technology
Inflatable, rigidizable or mechanical structure with surface mesh or membrane
- Spin Scanned Reflector
- Spin-Scanned Feed
- Push-Broom

### Illustration of Technology

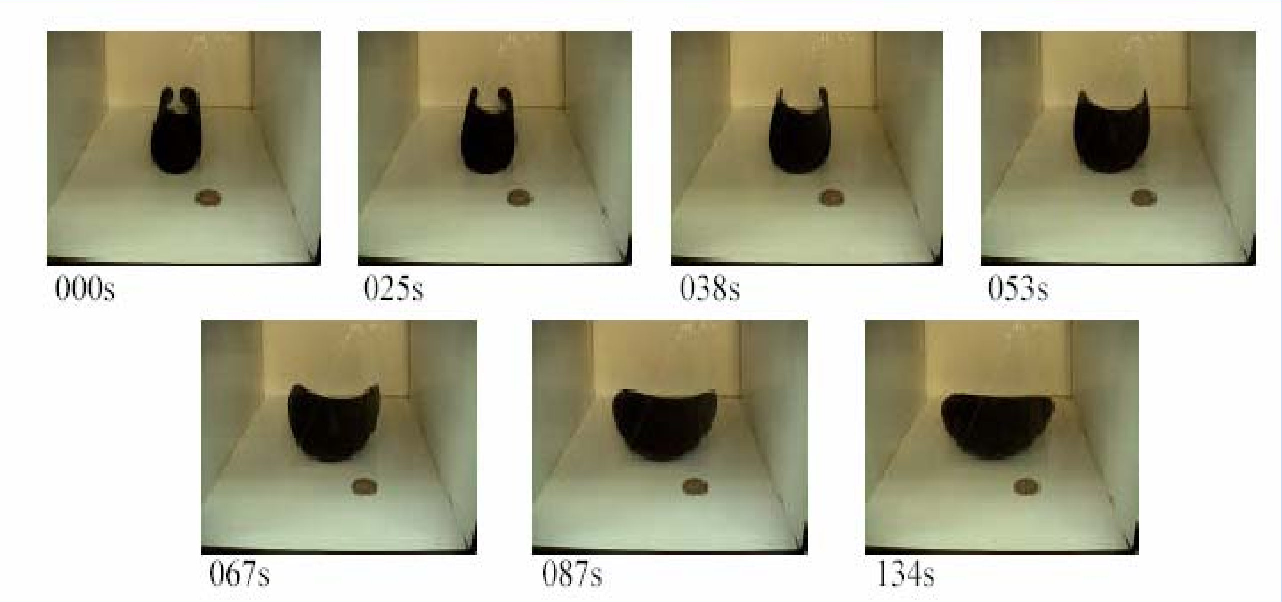


Rain Radar based on a 5 x 5 m cylindrical push-broom antenna

ESE Tech - 6

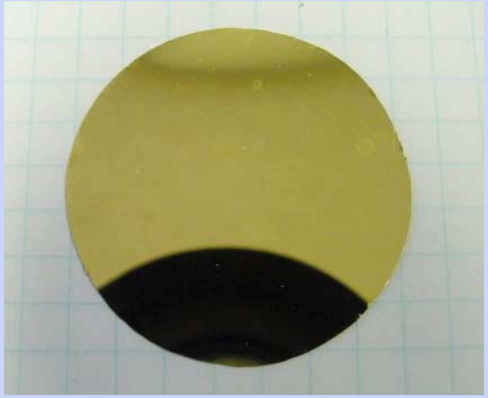
# Why Consider Shape Memory Composite Reflectors?

- Replication – Reduced production time and cost
- Larger design parameter space; low mass, compact packing, high stiffness, segmented or monolithic
- Adaptable to simple in-space deployment and active control
- Better surface accuracy than mesh and inflatable

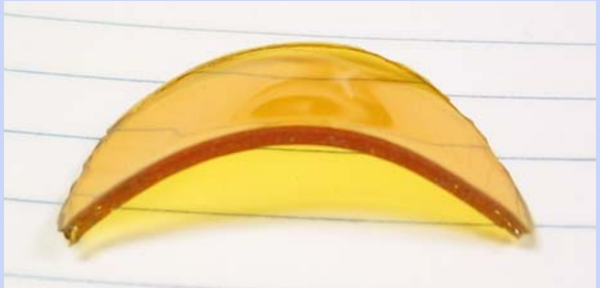


# Laminated Reflector Concept
# Replicated Nickel/Composite

- **Surface Replication: low stress nickel**
  - Replicates optical figure
  - Good surface finish (<2nm RMS)
  - Tough, flexible, established processes
  - Etched for reliable adhesion



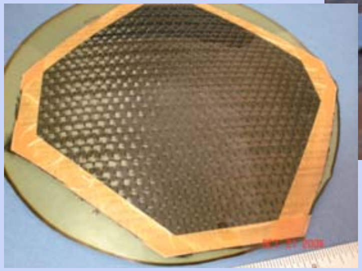
- **Shape memory resin composite**
  - High stiffness, low mass (1-5 kg/$m^2$)
  - Replicated Production
  - Low outgassing (< 0.16% TML)
  - Deployable
  - Resin ratio adjusted to match nickel CTE



# Ball Aerospace, CRG, Northwestern Univ. Responsibilities

- **Ball Aerospace**
  - —Concept development and evaluation
  - —Integrated Modeling
  - —Application engineering


- **Cornerstone Research Group**
  - —Specialized shape memory polymer tailoring
  - —Composite reinforcement
  - —Fabrication of composites

- **Northwestern University**
  - —Electroplated optics fabrication
  - —Nickel etching, coatings
  - —Materials research expertise

# Extensive process development and controls required

- **Key Problems for reflector manufacture:**
  - Manage the interface stress between the composite and nickel for adhesion and shape control
  - Deployment hysteresis
  - Material stability
- **Addressed through:**
  - Thermal and Structural Modeling of the composite structure and nickel
  - Electroplating process control for low stress plating and rear surface treatment
  - Composite resin and process selection
  - Composite structure development: fiber selection and orientation; resin fillers

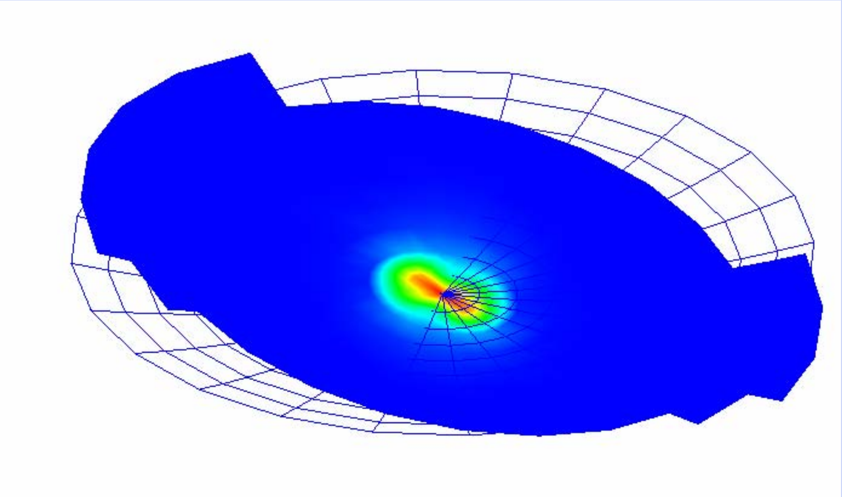
# Detailed Modeling Goals

- **Update material constructions**
  - Symmetric laminations for stability and uniformity
- **Comparison with strain measurements made on samples**
  - New constructions fabricated and tested
- **Scalability**
  - Utilize scaling methods developed for other large space structures
- **Thermal deformations**
  - Balanced constructions minimize thermal deformation level
- **Resonant Frequency**
  - Mass / size are drivers for fibers, thickness, # layers, deployability
- **Thermal actuation**
  - Analysis demonstrated feasibility of deployment via solar heating, with appropriate thermal coatings

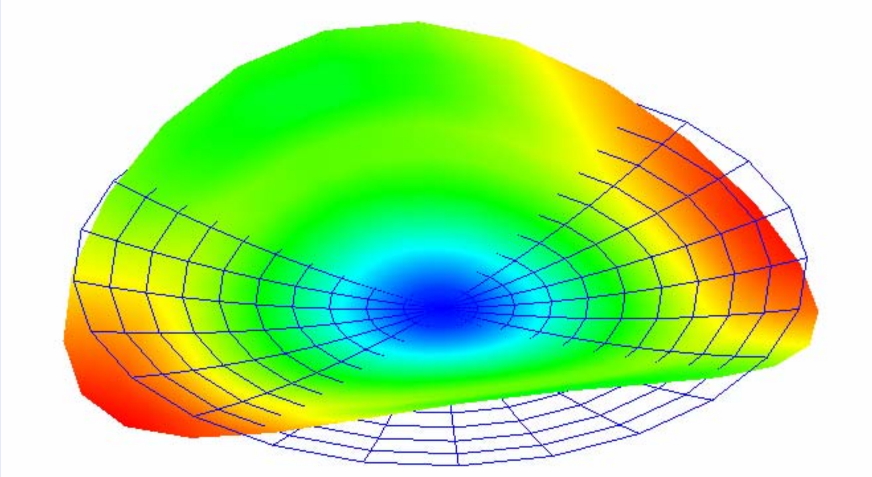
# Resonant Frequency for a 30 cm Mirror

| Material | F1 (Hz) | F2 (Hz) | F3 (Hz) | F4 (Hz) |
|---|---|---|---|---|
| T700 | 30.3 | 42.5 | 72.3 | 105. |
| M55J | 38.7 | 58.0 | 90.6 | 148. |
| K13C2U | 47.1 | 72.9 | 111. | 191. |

First and Second Mode Shape



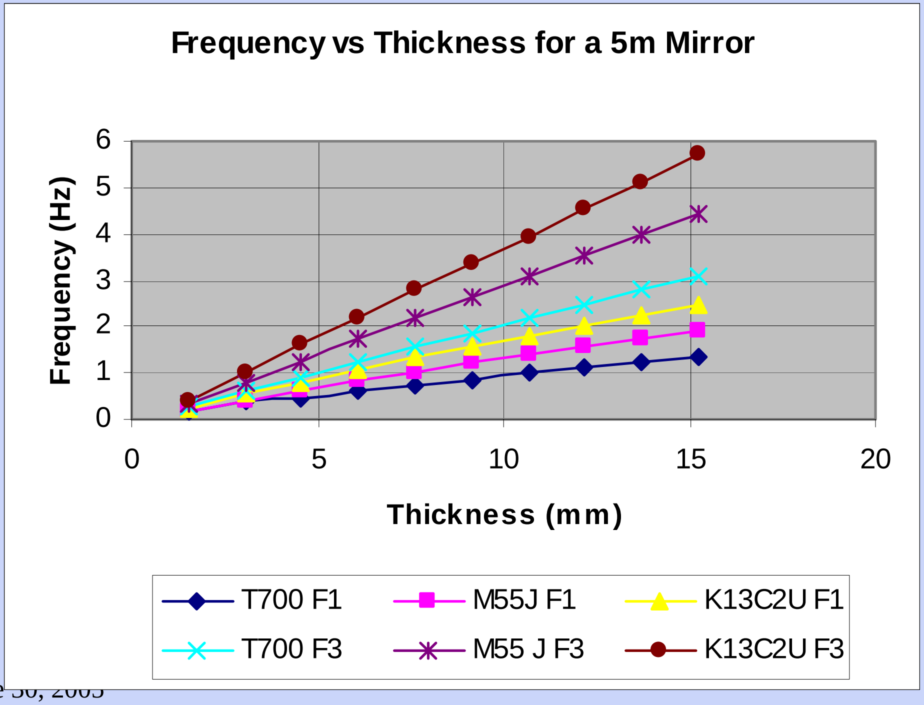
Third and Fourth Mode Shape



# Resonant Frequency for a 5m Mirror

**Using the same (0.060 in) thickness:**

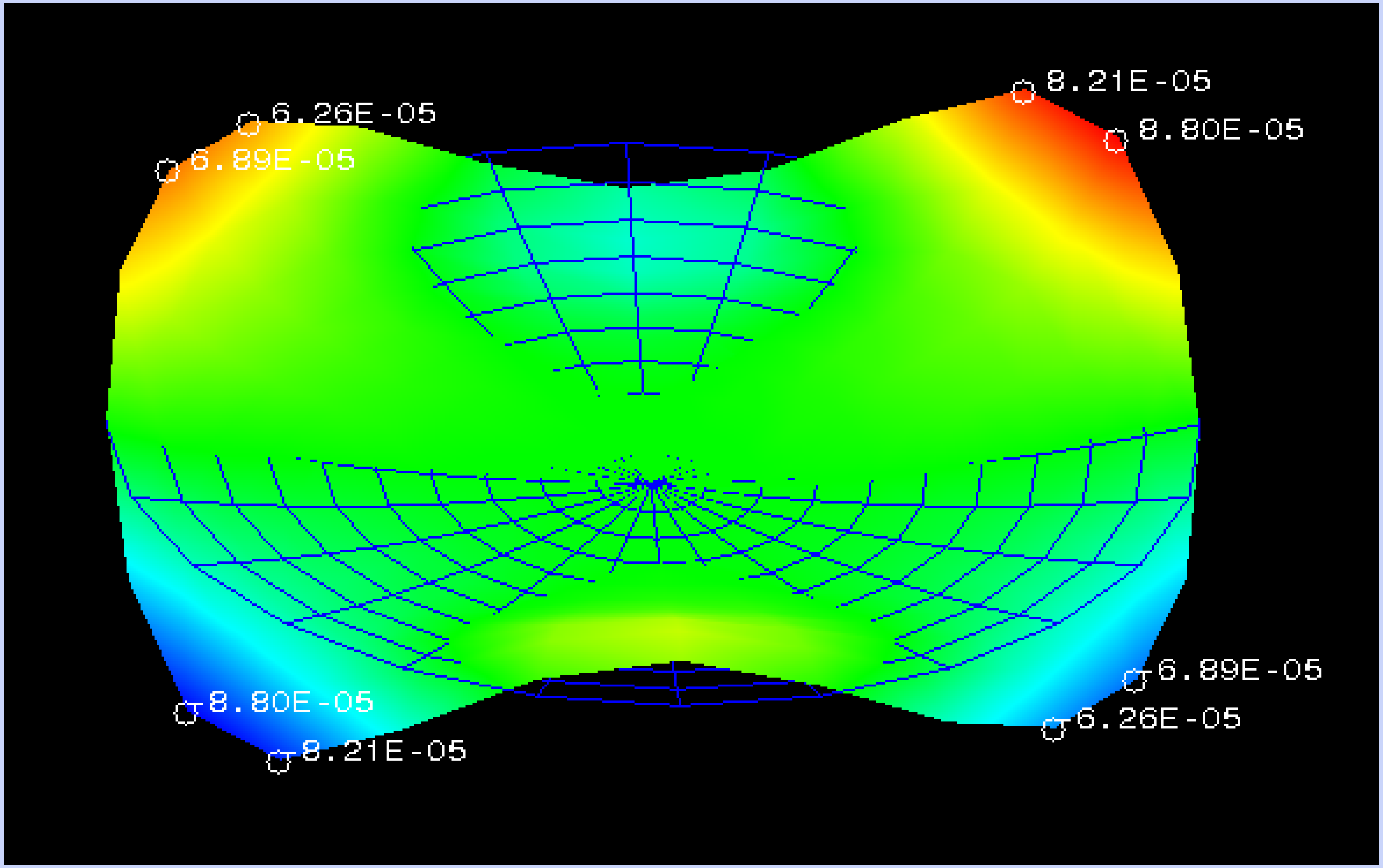
| Material | F1 (Hz) | F2 (Hz) | F3 (Hz) | F4 (Hz) |
|---|---|---|---|---|
| T700 | 0.145 | 0.290 | 0.268 | 0.399 |
| M55J | 0.191 | 0.298 | 0.338 | 0.565 |
| K13C2U | 0.239 | 0.386 | 0.415 | 0.736 |




5m Mirror Mass:
(from NASTRAN FEM)
1.5 mm thick: 58 kg
7.6 mm thick: 274 kg
15 mm thick: 544 kg

# Shape Change for a ±1° Side to Side Gradient are minor effect

### Deformed Shape for a T700 Mirror with Ni Coating

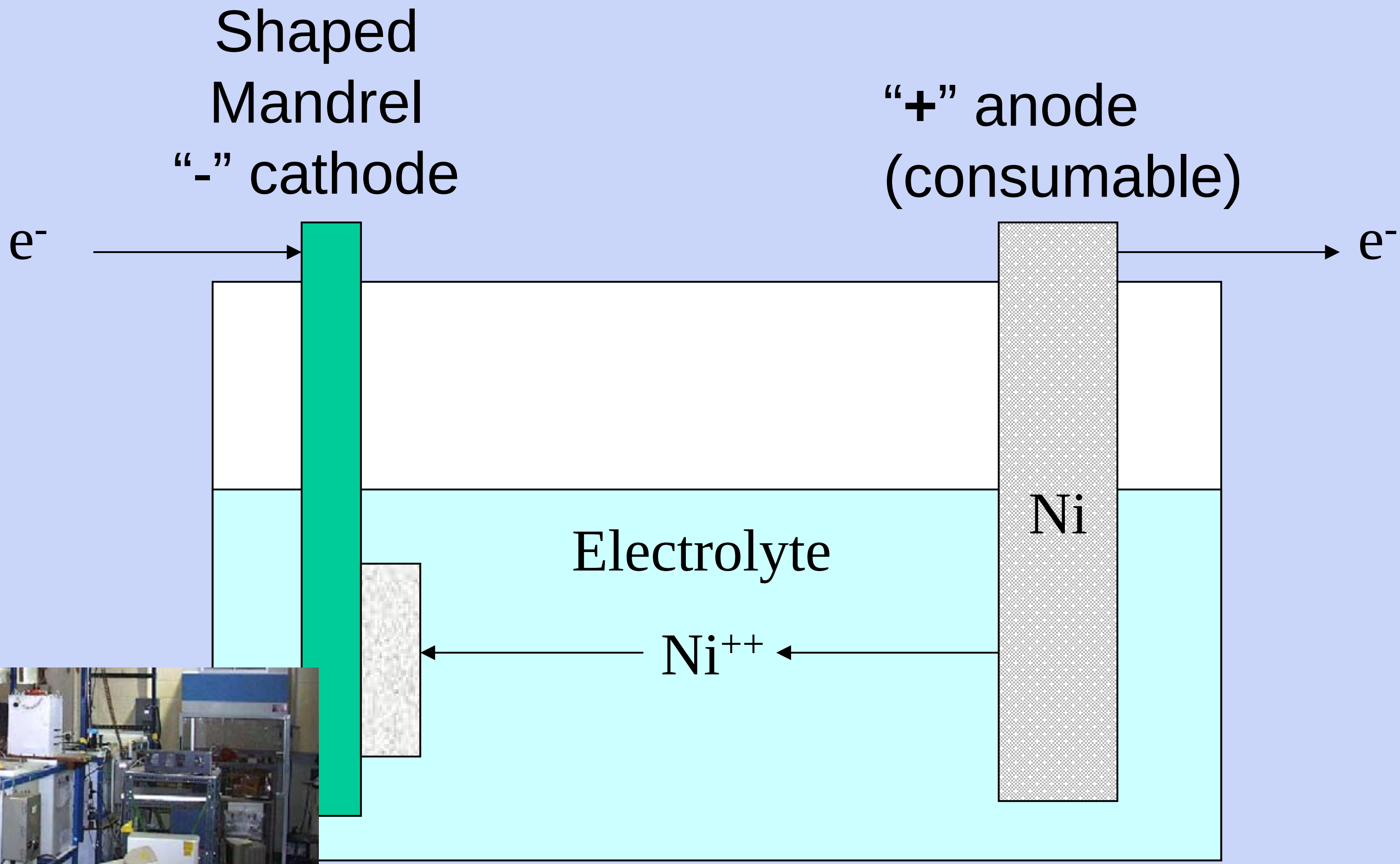



Displacements in inches

# Replication process

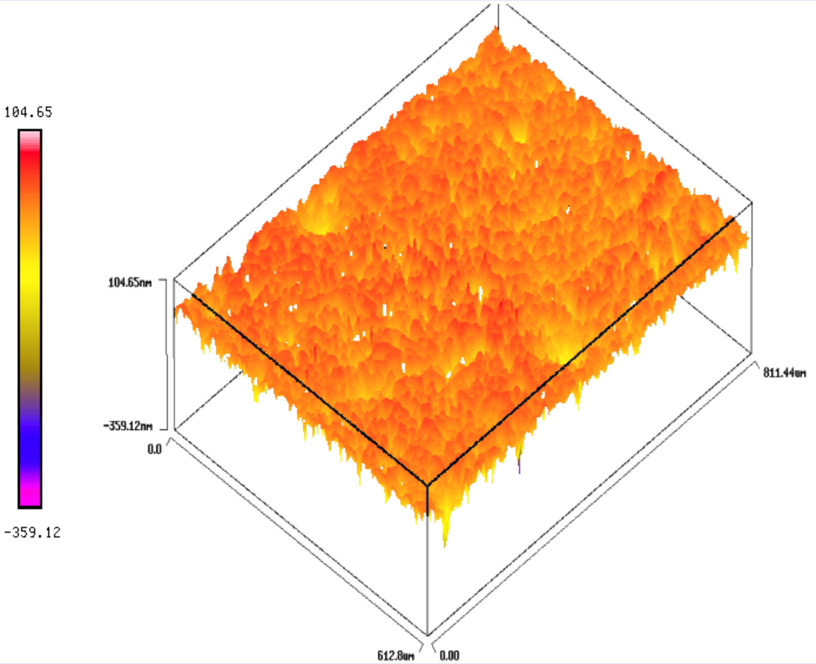

- Polish and prepare mandrel
- Electroplate Nickel
- Etch Nickel for adhesion
- Lay-up and cure composite
- Remove from Mandrel
- Characterize surface
- Prepare for stow and deploy testing and further measurement

# Low Stress Electroplating Forms the Reflective Surface




**Process adapted from fabrication of Wolter X-Ray optics**

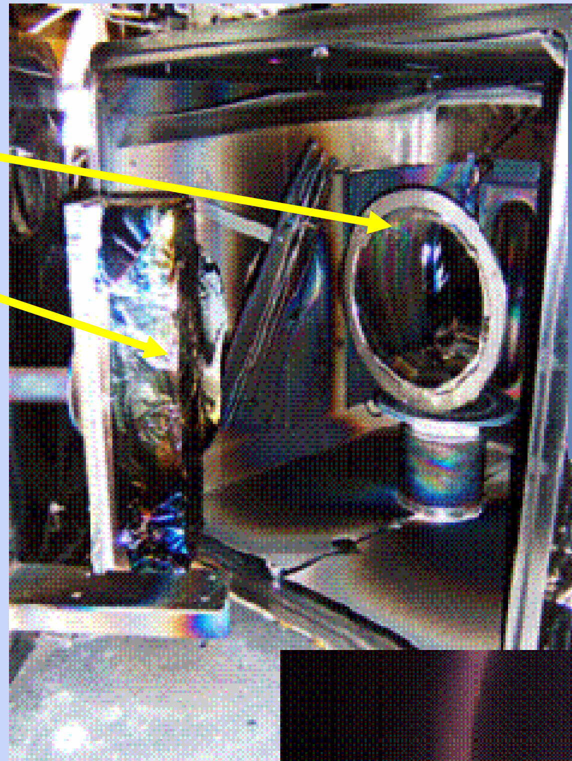
# Surface roughness replication achieved 2nm RMS




Zygo interferometer scan data from a developmental cyanate ester resin cast sample.

**Zygo interferometer scan data shows nickel can meet at least 2 nm roughness**

# Plasma Etching Prepares Nickel Electroforms for Composite

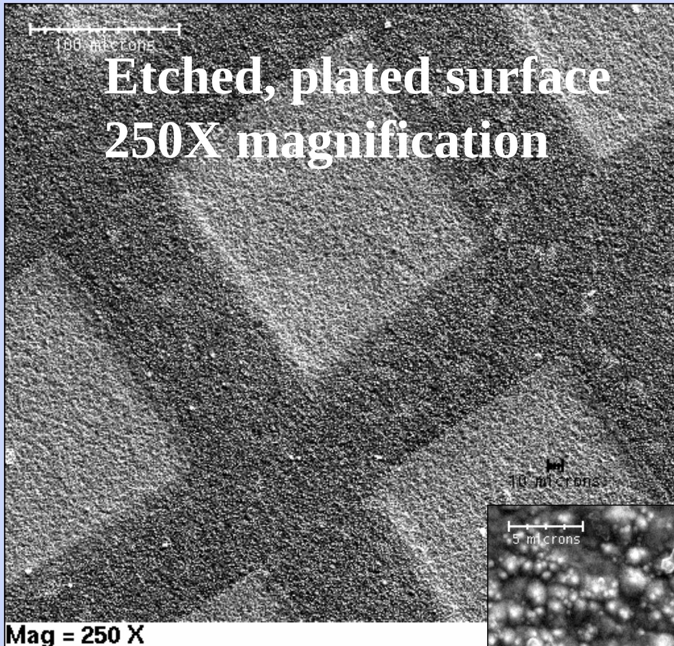


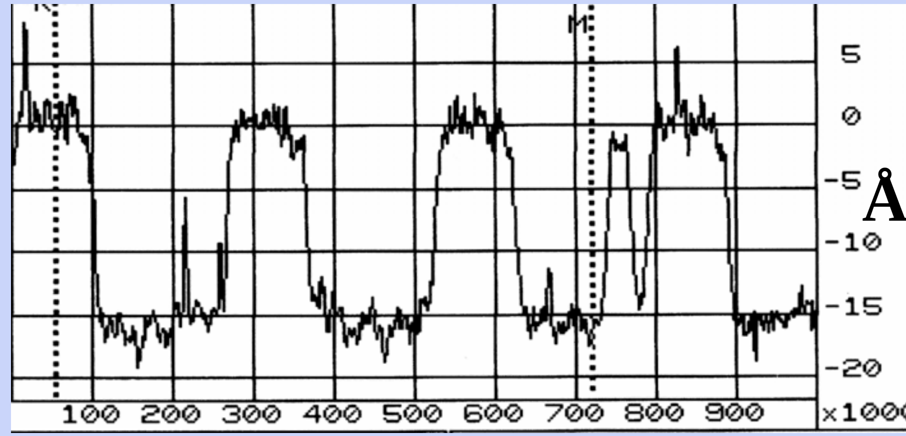
- Fixture and mirror mandrel
- The cathode structure and sputtering target

Rear surface of 30cm plasma-etched electroform

- The plasma etching viewed through a quartz window
- Color is characteristic of the argon plasma

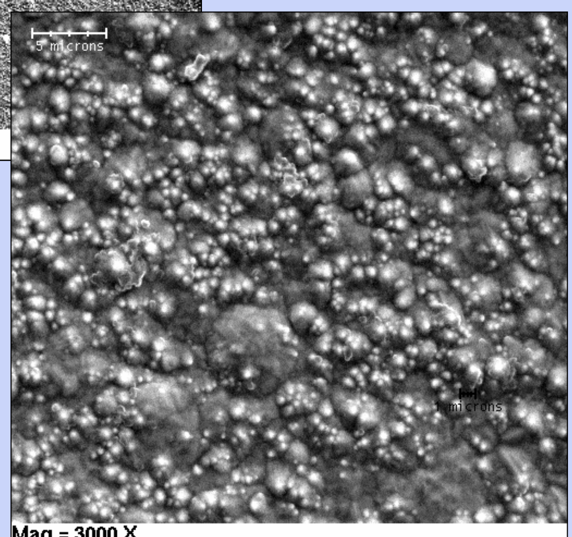
# Etching of Nickel Increases Roughness Profile and Improves Adhesion



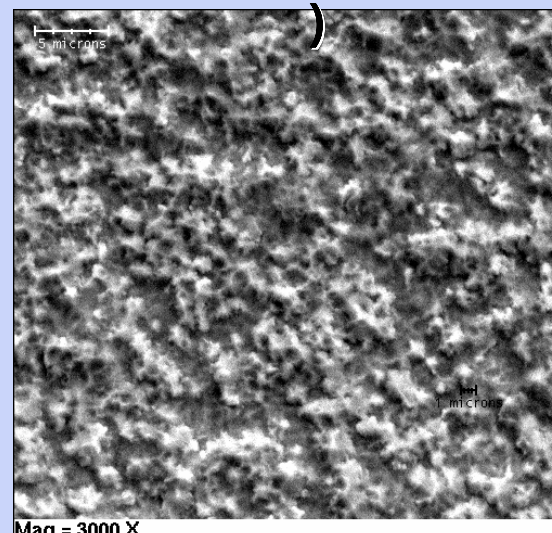




Mesh Profile (microns)

3000 X magnification




As-plated



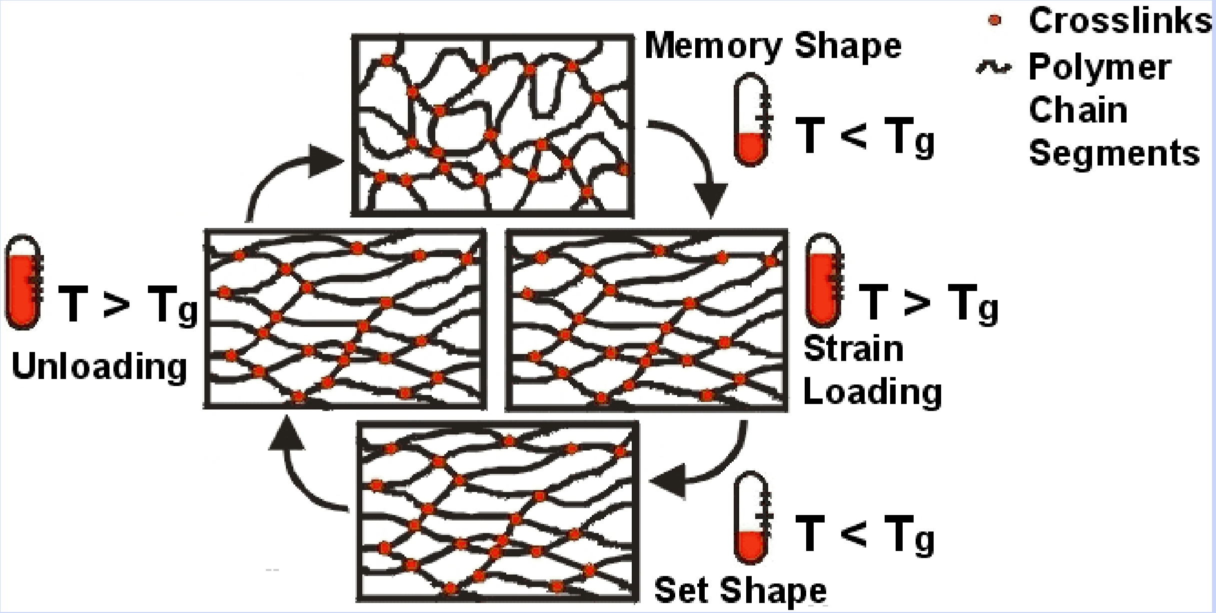

Etched

# Shape Memory Polymers
## Application

**Cured shape---**

**Stow/Deploy actuation--**

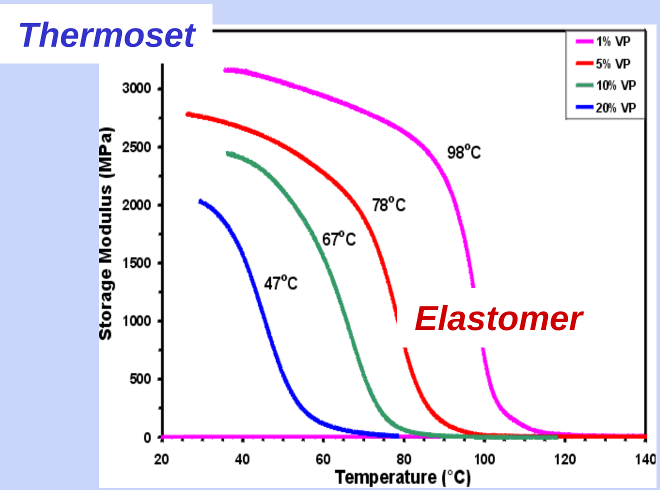
**Stowed ---**




- **Replication**
  - Replicate surface from master in manufacturing processes
- **Actuation**
  - Store and release mechanical energy
- **Reconfiguration**
  - Temporary modulus reduction to enable shape change

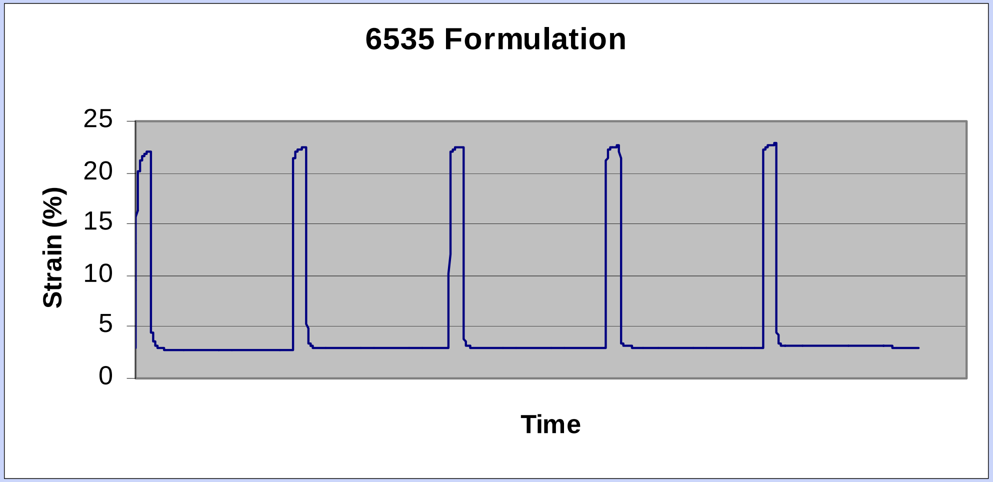
# SMP Development - Cyanate Ester

- **CE polymers are already used in space**
- **Conventional CE transformed to SMP**
  - Fully cured, cross-linked for stability
  - Required new polymer design
- **CE shape memory polymer results:**
  - Deformation-recovery cycle demonstrated
  - Activation temperature of 160°C
- **Improvements Continuing**
  - Enhanced strain recovery
  - Increased toughness




***Cyanate Ester SMP***

**More uniform recovery from 23% strain achieved. Tg = 174 °C**



# Cyanate Ester Shape Memory Resins- Acceptable Outgassing

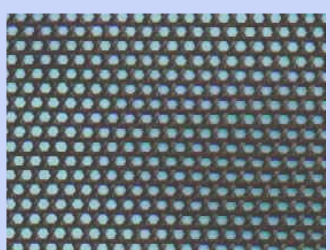
- Total Mass Loss (TML) and Condensed Outgassing Product (COP) tests on cyanate ester SMP and composites found them to be space-qualifiable

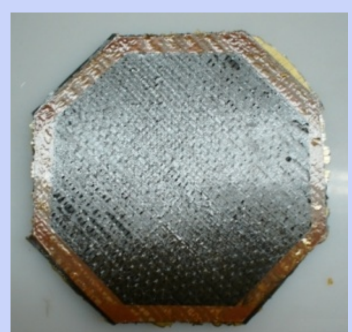
| Log # | Material | TML % | COP % |
|---|---|---|---|
| 58 | SynLam TM with 3D Carbon Fabric | 0.292 | 0.027 |
| 59 | Triaxial weave Carbon Composite | 0.059 | 0.012 |
| 66 | Neat CE SMP Resin | 0.147 | 0.006 |
| **-** | **Acceptable levels** | **1.0** | **0.1** |

# Reinforcement Materials Investigated

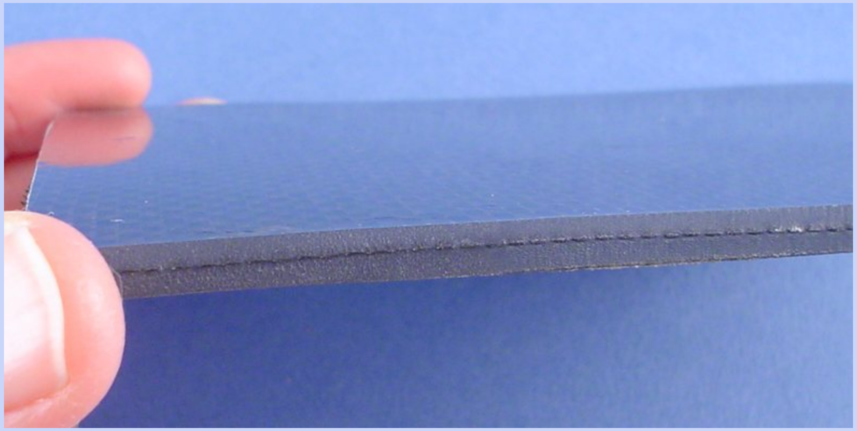
| Fabric Material | Tensile Strength (MPa) | Tensile Modulus (GPa) | Strain% | Density (g/cc) | CTE% |
|---|---|---|---|---|---|
| T300, | 3530 | 230 | 1.5 | 1.76 | -4.1 |
| T700, 0,±60 | 4900 | 230 | 2.1 | 1.8 | -3.8 |
| 1K 0,±60 Open Weave | 3875 | 233.5 | 1.65 | 1.76 | -4.1 |

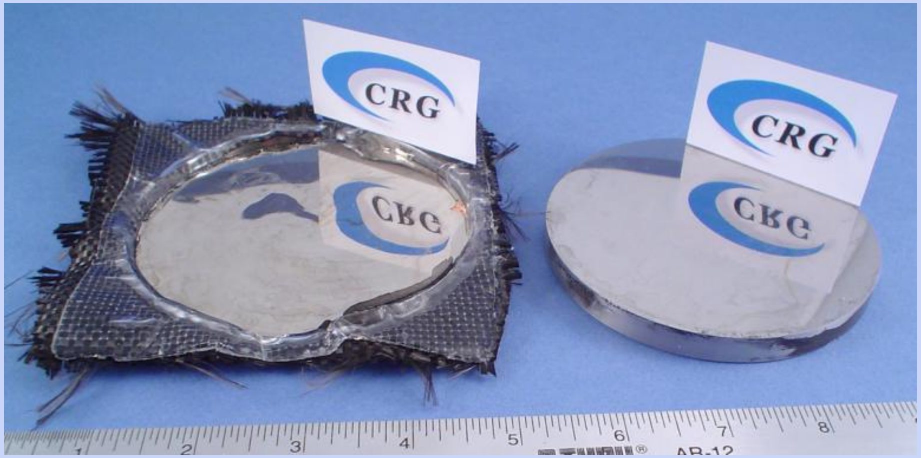
| Microspheres | Average Particle Size (μm) | Average Particle Density (g/cc) | Strength (MPa) |
|---|---|---|---|
| Glass | 55 | 0.25 | 6.89, 40% Collapse |
| Carbon | 55 | 0.4 | - |
| Phenolic | 70 | 0.11 | 6.89 |





# Print through remains a challenge, but is significantly reduced



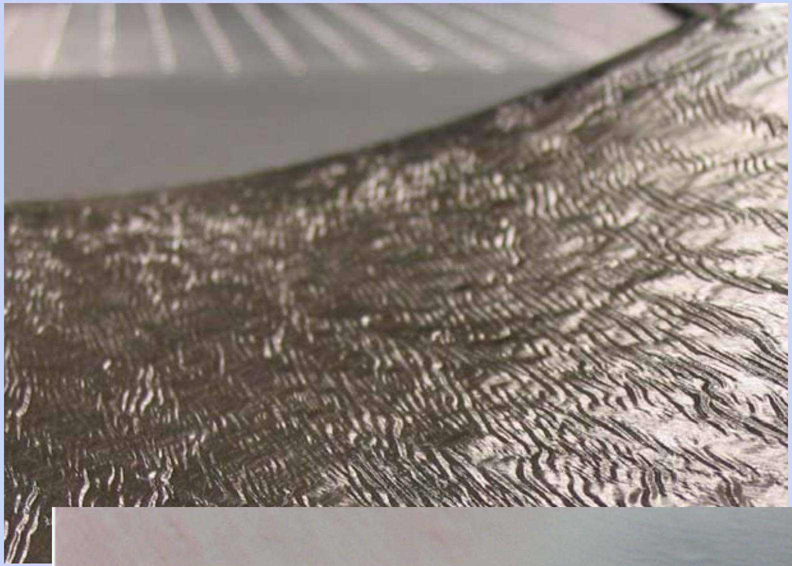


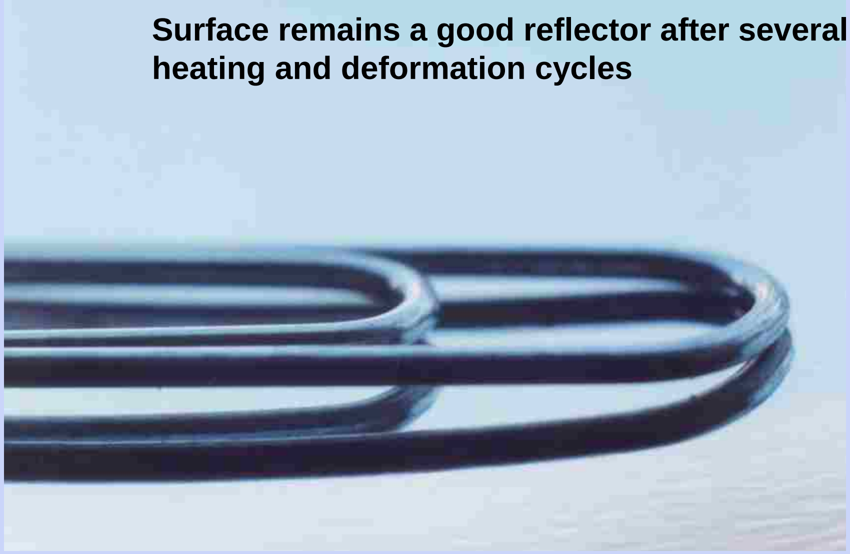

- **Fiber-resin CTE mismatch produces print through**
- **Sandwich approach is improvement, without fibers near surface**
- **Neat (resin rich) layer surrounds fiber reinforcement**
- **Nanofibers and alternate filler reinforcement being investigated**

- **Neat resin layer reduces fiber print-through effect, but nickel-thermal mismatch caused waviness**

# Deployed Mirror surface undamaged by deployment

- **Buckling was observed <u>only</u> where delaminated**
- **Remains smooth after several heat cycles**
- **Underlying fibers and resin undamaged**

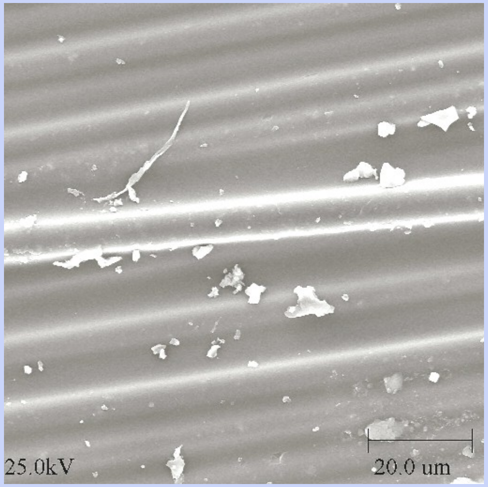


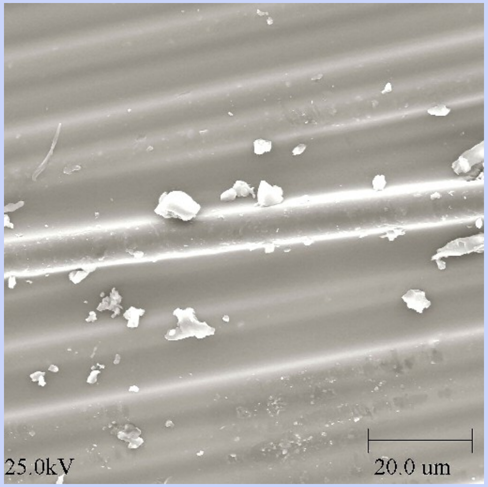
# Composite Thermal & Bending Fatigue Test

- **Thermal Cycling showed no damage or changes**

**Samples of composite have been temperature cycled 10x between –20C to +50C.**




**1000x SEM before cycling**

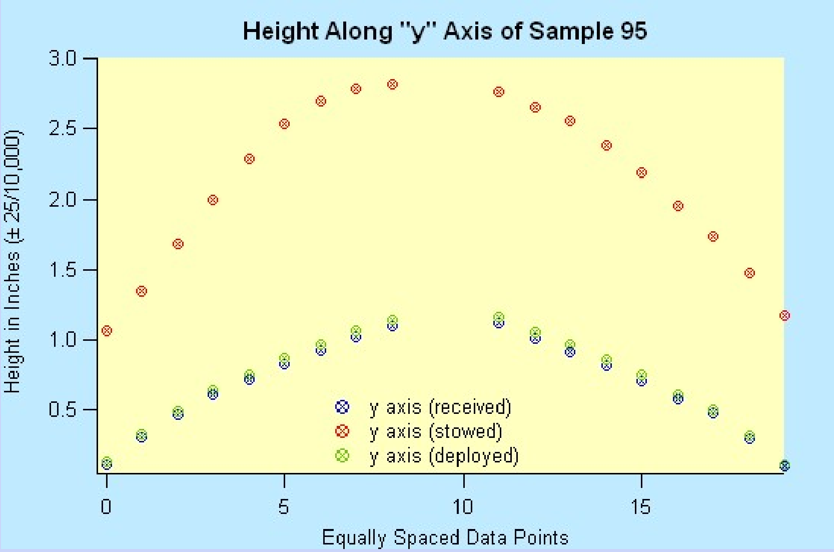


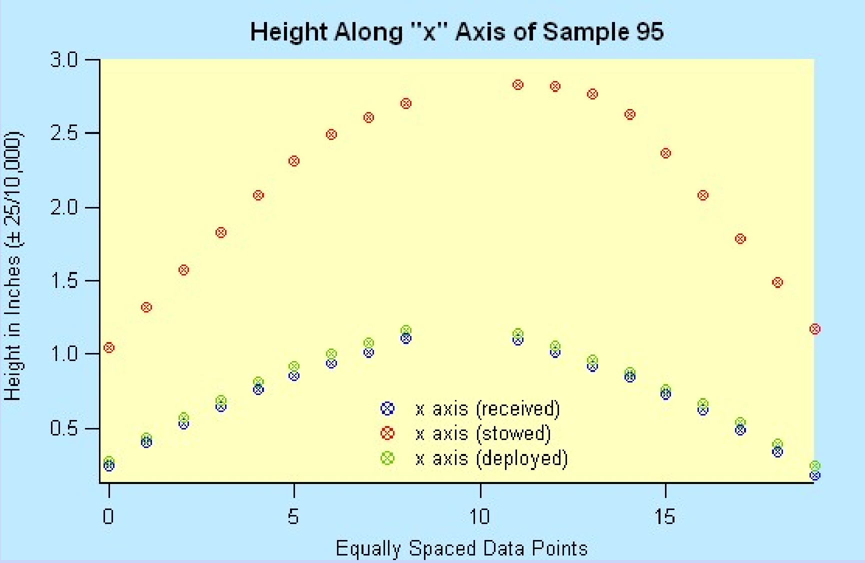

**1000x SEM after cycling**

**SEM photos before and after from 25x to 3000x show no change or microcracking in the resin or fibers. Microscope inspection of composite samples subjected to repeated cycling from room temperature to +200C have not shown evidence of resin of fiber cracking.**

# Shape Memory Reflector Feasibility Demonstrated

- **<u>Figure</u>: Low stress nickel process produces <10 waves PTP mirror. Composite replication needs further development**
- **<u>Roughness</u>: Low scatter nickel achieved 2nm RMS**
- **<u>Outgassing</u>: Shape Memory CE resin meets requirements (0.16% TML)**
- **<u>Spherical Surfaces</u>: Reinforced composite SMP applied to flat and spherical nickel plating surfaces**
- **<u>Adhesion</u>: Demonstrated ruggedness of nickel-composite lamination**
- **<u>Stow and deployment</u> demonstrated without damage to optical surface, deployment repeatability needs development**



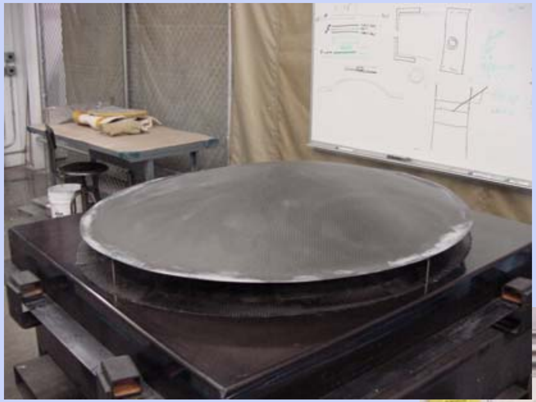



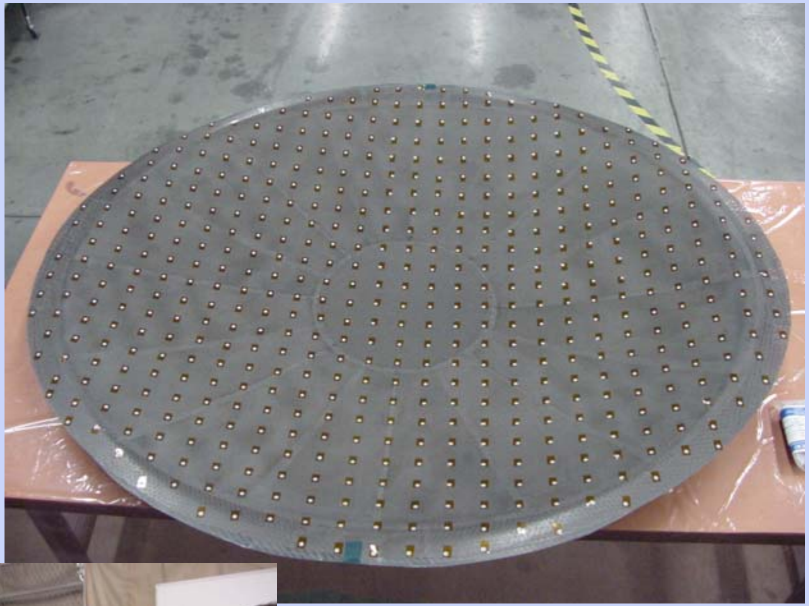
# 1m reflector optics in development

**Areal Density 0.4 kg/m$^2$**

**Carbon fiber Triax Weave**

**Surfaces << 1mm**





# Conclusions

- **Laminated nickel – composite optics can provide deployable, highly reflective surfaces without delamination or deterioration of metal surface and substrate**
- **Typical deployment accuracy is consistent with needs for 15GHz microwave reflectors of 1-2 meter diameter, and further development for surface accuracy adequate at higher frequencies**
- **Additional work needs to be done in:**
  - Resin chemistry (greater elongation, low CTE, low temp cure)
  - Structures (optimizing deployment, modeling in stow condition)
  - Durability verification in the space environment

# Acknowledgements

Valuable contributions to this work were made by Lisa R. Hardaway, Gary Emerson, Kris young, Bruce Snyder, Duane Hill, and Andy Zundel at Ball Aerospace, Michael Graham, Jonathan Echt, Matvey Farber, and Semyon Vaynman at Northwestern Univ., and Jason Hermiller, Matt Everhart, Robert Schueler, Thomas Barnell, Michael Groseclose and Stephen Vining at CRG, Inc.

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